

about 1 to about 10 Å/minute until a thickness of about 100 Å to about 300 Å has been deposited. As described in further detail hereinafter, such an electrically-conductive-non-metallic-layer/semiconductive-organic-layer interface is capable of providing a low-resistance electrical contact for use in an OLED as well as for other types of optoelectronic devices.

[0059] The present invention is, thus, more specifically directed to a new class of highly transparent organic light emitting devices (OLEDs) employing a non-metallic cathode. OLEDs that make use of a non-metallic cathode have a very low reflectivity and a high transparency that is close to the theoretical maximum that can be achieved for a multi-layer organic structure. The low-reflectivity of such OLEDs may be particularly beneficial for use in high contrast display applications as well as for use in eliminating microcavity effects in stacked organic light emitting devices (SOLEDs). OLEDs employing these low resistance non-metallic cathodes are expected to be particularly useful in reliable high-resolution full color flat panel displays, "heads-up" displays and organic-based lasers.

[0060] As a representative embodiment of the present invention as shown in FIG. 2a, a TOLED is deposited on a glass substrate pre-coated with a film of indium tin oxide (ITO) which serves as the transparent hole injecting anode. The TOLED includes, for example, a non-metallic cathode 1, an electron injecting interface layer 6, an electron transporting layer 2, a hole transporting layer 3, an anode layer 4 and a substrate 5. After depositing a hole transporting layer and an electron transporting layer, the electron injecting interface layer is added by depositing, for example, a thin film of copper phthalocyanine (CuPc) which is then capped with a film of low-power, radio-frequency sputtered ITO. This second ITO layer functions as the cathode of this device. In addition to functioning, in some cases, as a protection layer that prevents damage to the underlying organic layers during the ITO sputtering process, the CuPc layer also functions in combination with the ITO layer as the electron injecting region for delivering electrons to the adjacent electron transporting layer. An additional intermediate electron transporting layer of 4,4'-di(N-carbazolo)diphenyl (CBP), for example, may be present between the first electron transporting layer and the CuPc layer, as shown in FIG. 2b. The intermediate electron transporting layer lies between the electron injecting interface layer that is in low-resistance electrical contact with the non-metallic cathode layer and the electron transporting layer that is in contact with the hole transporting layer. In particular, the OLED of FIG. 2b includes a non-metallic layer 1, an electron injecting interface layer 6, an intermediate electron transporting layer 7, an electron transporting layer 2, a hole transporting layer 3, an anode layer 4 and a substrate 5.

[0061] Due to the absence of a metallic cathode layer, the representative Alq₃-based TOLEDs disclosed herein emit nearly identical light levels in the forward and back scattered directions with a total external quantum efficiency of about 0.3%. These devices are over 80% transmissive in the visible. The reflection and absorption characteristics, current-voltage, luminance-current, and electroluminescence spectra of OLEDs prepared according to the present invention demonstrate performance characteristics that are at least comparable with and in certain respects superior to conven-

tional TOLEDs that employ a more reflective cathode comprised of a thin film of Mg:Ag capped with ITO.

[0062] For example, as shown by a comparison of the TOLED results shown in FIG. 3 with FIG. 4, TOLEDs according to the present invention show only about a 2-fold drop in light output at 180 hours, whereas prior art TOLEDs have about a 4-fold drop in light output over the same time interval. The results in FIG. 5 show that the phthalocyanines of both Cu (CuPc) and Zn (ZnPc) may be used as the electron injecting interface layer, though the results in FIG. 6 show that the CuPc device has a significantly higher quantum efficiency. A comparison of the results in FIG. 8 with the results in FIG. 9 shows that the stability of the I-V characteristics of OLEDs made according to the present invention is comparable to prior art devices. The results shown in FIG. 7 show that the total light transmission of an OLED made according to the present invention is near the theoretical maximum of what can be achieved for an OLED, except for that part of the spectrum which shows the Q-band absorption structure characteristic of CuPc. The reflection spectrum of this device approaches the theoretical minimum as limited by the glass/air and ITO/air interfaces. Anti-reflection layers can further reduce this reflection to a negligible value.

[0063] The electron injecting interface layer that is in contact with the ITO layer may have a thickness ranging from about 15-120 Å. For example, FIGS. 10 and 11 show that whenever CuPc is used as the electron injecting interface layer, devices having a CuPc injection layer thickness from about 30 Å to about 120 Å produced comparable performance characteristics. The devices that were prepared to collect the data shown in FIGS. 10 and 11 also included a CuPc layer with a 50 Å thickness between the ITO anode layer and the hole transporting layer. This CuPc layer, which is in contact with the ITO anode layer, functions as a hole injection enhancement layer, such as disclosed in co-pending application having Ser. No. 08/865,491, filed May 29, 1997.

[0064] As further examples for representing the scope of the present invention, the current-voltage (I-V) characteristics of another typical transparent organic light emitting device having the non-metallic cathode and a conventional TOLED grown in the same run are shown in FIG. 12. The TOLED that was used to obtain the results shown in FIG. 12 is shown in FIG. 13, wherein the non-metallic cathode 1 was ITO, the electron injecting interface layer 6 was CuPc, the electron transporting layer 2 was Alq₃, the hole transporting layer 3 was α-NPD, the anode layer 4 was ITO and the substrate 5. This device included an additional CuPc layer 8 between the ITO anode and HTL. Two distinct regions of operation are observed, above and below the "turn-on voltage", V_T . Below V_T , trap-free, space-charge limited transport follows $I \propto V^{m-1}$. Above V_T , the current is trapped-charge-limited following $I \propto V^{m-1}$. P. E. Burrows, S. R. Forrest, *Appl. Phys. Lett.* 64, 2285 (1994), P. E. Burrows, Z. Shen, V. Bulovic, D. M. McCarty, S. R. Forrest, J. A. Cronin, and M. E. Thompson, *J. Appl. Phys.* 79, 7991 (1996). The slightly less efficient injection properties of the ITO/CuPc as compared to those of the ITO/Mg:Ag contact are reflected in the nominal difference in V_T for the TOLED (4.2 V) and non-metallic-cathode-containing TOLED (5.2 V). Similar I-V characteristics are obtained when the CuPc in the cathode is replaced with ZnPc, indicating their equivalence